Advanced computational thermal fluid physics (CTFP) and its assessment for light water reactors and supercritical reactors

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The **objective** of this ***Korean/U.S. laboratory/university collaboration*** of coupled fundamental computational and experimental studies is to develop supporting knowledge needed for improved predictive techniques for use in the technology development of ALWR (Advanced Light Water Reactor) and SCR (Super Critical pressure Reactor) concepts and their passive safety systems. This basic thermal fluids research applies first principles approaches (Direct Numerical Simulation—DNS and Large Eddy Simulation—LES) coupled with experimentation (heat transfer and fluid mechanics measurements). DNS, LES and differential second-moment closures (DSM or Reynolds-stress models) are ***advanced computational concepts*** in turbulence "modeling" whose development is being ***extended to treat complex geometries and severe property variation*** for ALWRs and SCRs.

General effects of strong heating of liquid water are variation of the viscosity and, possibly, significant buoyancy effects depending on the geometry. **General effects of strong heating** of superheated steam and supercritical water **are variation of all transport properties**, reduction of density causing **acceleration** of the flow in the central core **and**, in some cases, significant **buoyancy forces**. As a single example of consequent application problems, general-purpose commercial Computational Thermal Fluid Dynamic (CTFD) codes do not necessarily provide accurate or conservative predictions for these conditions, as shown by the comparisons of Figure 1. This figure presents predictions from several popular turbulence models which are employed in commercial codes. (While a knowledgeable turbulence modeler might adjust the model so that the predictions agree with the data, the results would not likely be useful beyond the particular situation—and the normal design engineer does not possess that level of expertise.) Growth of the internal thermal boundary layer leads to readjustment of any previously fully-developed turbulent momentum profile. No truly fully-established conditions are reached because the temperature rises—leading, in turn, to continuous axial and radial variation of properties such as the fluid viscosity.

Idealized flow geometries are often not found in the reactor cores of light water reactors, either conventional PWRs and BWRs or advanced versions, such as SCRs. There are end plates, grid spacers with and without a variety of deflectors, closely-packed fuel rods, stagnant regions and other structures; some examples for supercritical water reactors are shown in Figure 2. Thus, the **flow geometry** is more **complex** than the geometries that have been used to generate the empirical correlations used in the thermal hydraulic safety codes. These complex geometries may augment the heat transfer and pressure drop or they may cause stagnation regions with reduced velocities and, thereby, increased thermal resistance leading to "hot spots." ***Detailed flow field measurements are needed to provide understanding of the interacting phenomena induced by these geometries.***

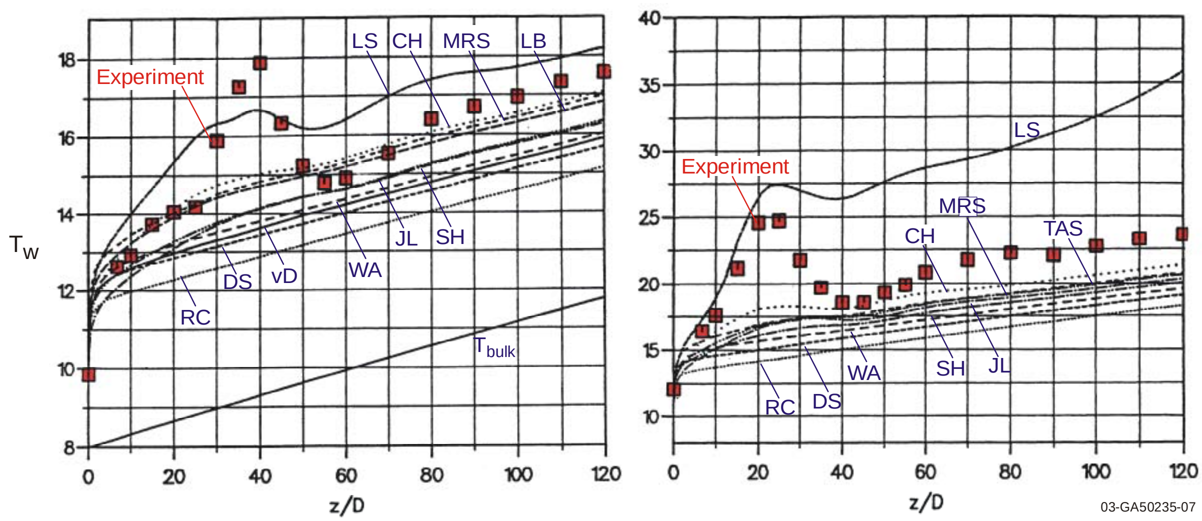

Fig. 1. Examples of difficulties in predicting surface temperatures in supercritical flows using popular turbulence models, arbitrary temperature units [Mikielewicz, 1994].

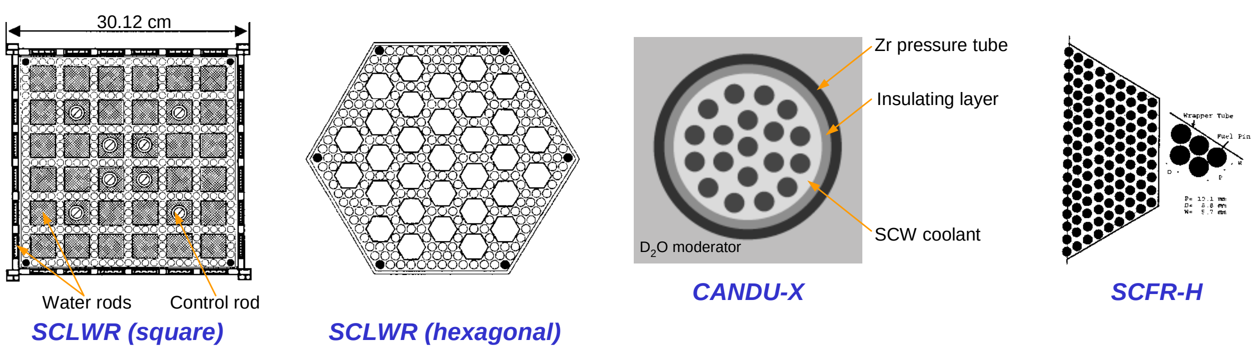

Fig. 2. Some proposed designs for fuel assemblies in Supercritical (pressure) Water Reactors.

Prof. Pletcher is extending LES to generic idealizations of such geometries; ***Prof. Yoo*** supports these studies with DNS. ***Prof. Park*** is developing DSM models. ***INEEL*** will obtain fundamental turbulence and velocity data for generic idealizations of the complex geometries of these advanced reactor systems. ***Profs. Wallace and Vukloslavcevic*** are developing miniaturized multi-sensor probes to measure turbulence components in supercritical flows. ***Profs. Lee, Ro, and Yoo*** will develop experiments on turbulence structure in superheated and supercritical flows. These tasks and their interactions are summarized in Figure 3.

The goals of the INEEL experimental portion of the study are to answer the scientific needs identified in the proposal and to guide code development and assess code capabilities for treating the generic forced convection problems in ALWRs and SCRs. The INEEL Matched-Index-of-Refraction (MIR) flow system will be employed; it will provide means for flow visualization and velocity measurements for the portion of the study dwelling on forced convection ***in complex reactor geometries***. For the candidate geometry, the experimental model provides a generic simulation of flow along a closely-packed array of fuel rods separated by periodic grid spacers.

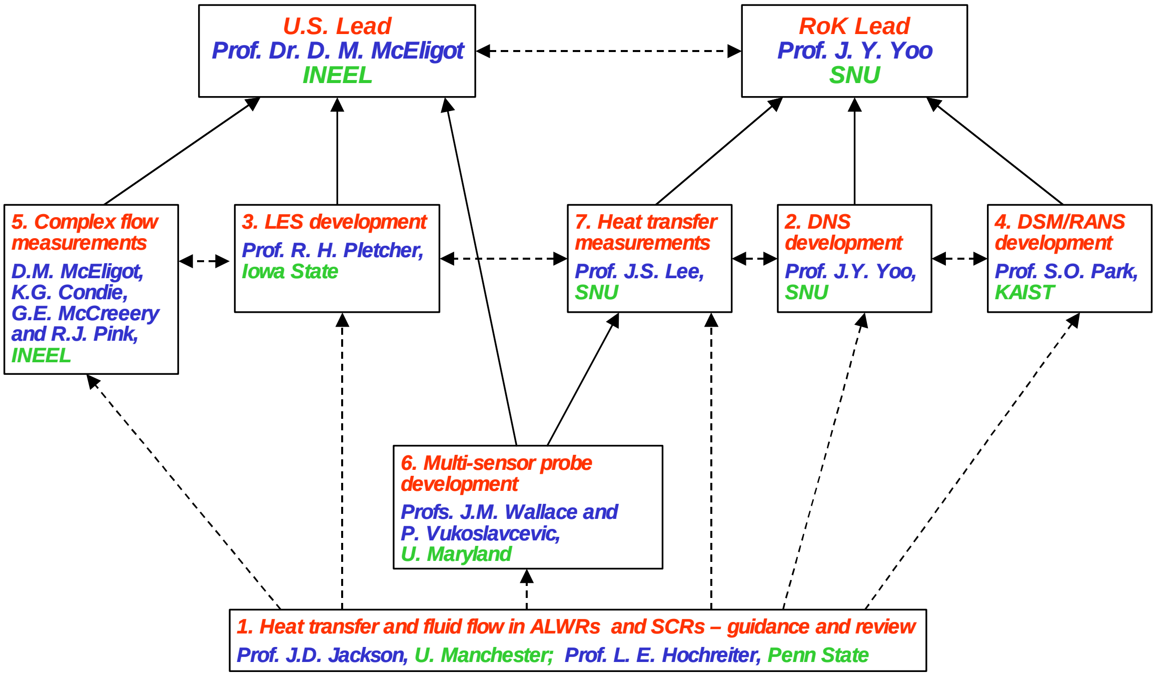

Fig. 3. Project organization chart.

For the **model** we have selected a two-rod configuration which includes some flow aspects of the thermal SCR concepts suggested by Oka et al. [2002], Forschungszentrum Karlsruhe [Cheng and Schulenberg, 2003] and INEEL [MacDonald et al., 2002] as shown in Figure 2a. We chose an idealized ring-cell spacer configuration to position the rods and to counter potential vibration (Figure 4); ring spacers [Kraemer et al., 1995] have been included in some SCFBR designs [Jevremovic, Oka and Koshizuka, 1996] as well as some boiling water reactor designs. Figure 5 provides an overview of the model relative to the MIR test section. In the region where the main measurements will be taken the material is predominantly quartz to match the refractive-index of our light mineral oil.

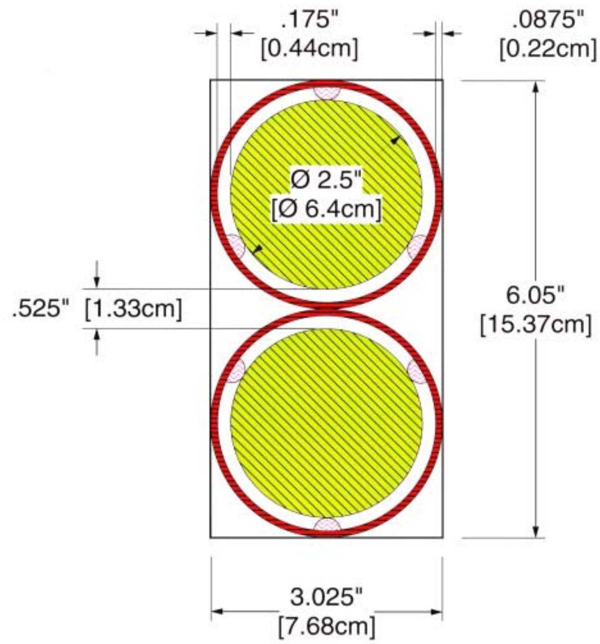

Fig. 4. Cross sectional view of model at the location of a grid spacer.

With a rod diameter of 2.5 inches (~ 6 cm), the geometry is scaled to be about six times larger than typical fuel pins. The thickness of the ring-cell spacer is about 1/6 the gap between rods (p-d) and its length is taken to be about ten times the annular gap between it and the simulated fuel rod. Three protuberances simulate dimples and a spring centering the rod. The axial spacing between the rings was chosen to be thirty times (p-d) to allow significant redevelopment and mixing of the flow; however, in some laminar flows this distance may not be sufficient to become fully-developed before the upstream influence of the next spacer is encountered. The model may be rotated ninety degrees so that all three velocity components may be measured with the LDV system. Figure 6 demonstrates the model as it will appear in the MIR test section with refractive indices matched.

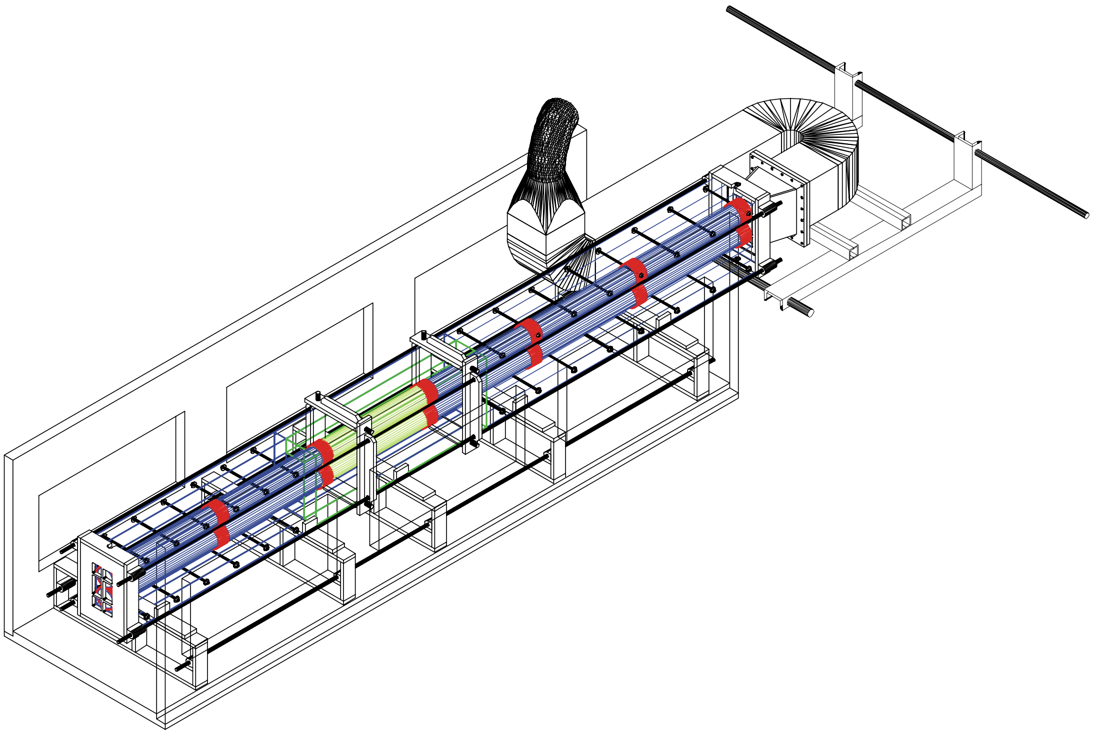

Fig. 5. Design configuration of model installed for experiment in the INEEL Matched-Index-of-Refraction flow system.

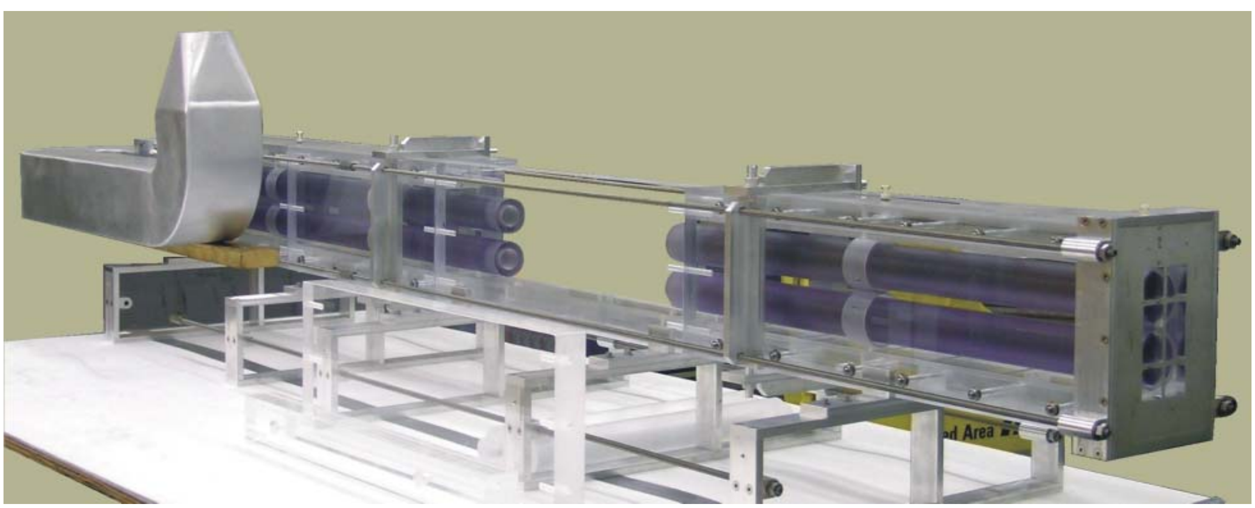

Fig. 6. View of assembled model (without quartz components for main measuring section).

References cited

Cheng, X., and T. Schulenberg, 2003. Design analysis of core assemblies for supercritical pressure conditions. ***Nuc. Engr. Design***, 223, pp. 279-294.

Jevremovic, T., Y. Oka and S.-i. Koshizuka, 1996. UO_2 core design of a direct-cycle fast converter reactor cooled by supercritical water. ***Nuc. Tech***., 114, pp. 273-284.

Kraemer, W., G. Proebstle, W. Uebelhack, T. Keheley, K. Tsuda and S. Kato, 1995. The ULTRAFLOW spacer -- an advanced feature of ATRIUM fuel assemblies for boiling water reactors. ***Nuc. Engr. Design***, 154, pp. 17-21.

MacDonald, P. E., J. Buongiorno, C. B. Davis and K. D. Weaver, 2002. Feasibility study of supercritical light water cooled fast reactors for actinide burning and electric power production. Tech. report INEEL/EXT-02-00925, June.

Mikielewicz, D. P., 1994. Comparative studies of turbulence models under conditions of mixed convection with variable properties in heated vertical tubes. Ph.D. thesis, Univ. Manchester.

Oka, Y., S.-i. Koshizuka, Y. Ishiwatari and A. Yamaji, 2002. Elements of design consideration of once-through cycle supercritical-pressure light water cooled reactor. ICAPP, Hollywood, Fla., June.

Annual technical report

McEligot, D. M., and twelve others, 2002. Advanced computational thermal fluid physics (CTFP) and its assessment for light water reactors and supercritical reactors. Tech. report INEEL/EXT-2002-1386, 10 December.

Topical reports

Bae, J. H., J. Y. Yoo and H. Choi, 2003. Direct numerical simulation of heat transfer to CO2 at supercritical pressure in a vertical tube. NuReTH-10, Seoul, 5-9 October.

Jackson, J. D., 2002. Consideration of the heat transfer properties of supercritical pressure water in relation to its use as a coolant in advanced nuclear reactors. Proc., 13th Pacific Basin Nuclear Conf., Shenzhen, China, 21– 25 October.

Jackson, J. D., K. O. J. Evans Lutterodt and R. Weinberg, 2003. Experimental studies of buoyancy-influenced convective heat transfer in heated vertical tubes at pressures just above and just below the thermodynamic critical value. Paper 1177, GENES4/ANP2003, Kyoto, 15-19 September.

McCreery, G. E., R. J. Pink, K. G. Condie and D. M. McEligot, 2003. Fluid dynamics of ribbed annuli. NuReTH-10, Seoul, 5-9 October.

Moro, J. P., P. V. Vukoslavcevic and V. Blet, 2003. A method to calibrate a hot-wire X-probe for applications in low-speed, variable temperature flow. ***Meas. Sci. Technol***., 14 pp. 1054-1062.

You, J., J. Y. Yoo and H. Choi, 2003. Direct numerical simulation of heated vertical air flows in fully developed turbulent mixed convection. ***Int J. Heat Mass Transfer***, 46, No. 9 (April), pp. 1613-1627.